

# Optical System Design

March 5, 2004

## Requirement

Horizontal direction

$W_p = 5 \text{ mm}$ ,  $\theta_p = 1 \text{ mrad}$ , both adjustable

Vertical direction

$W_{\perp} = 0.2 \text{ mm}$  variable,  $\theta_{\perp} < 3 \text{ mrad}$ .

## Light source

Nd:YAG, Continuum Powerlite Precision II 8030

Pulse repetition rate 30 Hz

Pulse width 6~8 ns

Pulse energy 650 mJ (fundamental, 1.06  $\mu\text{m}$ ), 150 mJ (third harmonic, 355 nm)

Linewidth 0.003  $\text{cm}^{-1}$  (90 MHz) with injection seeded.

$\lambda = 355 \text{ nm}$ ,

Assuming  $\theta_0 = 0.1 \text{ mrad}$ ,  $W_0 = \lambda/\pi\theta_0 = 1.13 \text{ mm}$ ,  $z_0 = W_0 / q_0 = 11.3 \text{ m}$ .

## Design objectives

- (i) Beam parameters (waist and divergence angle)
- (ii) Working distance from telescope to interaction region
- (iii) Pulse intensity at the window and lenses

## **I. Pre-collimation with circular lens**

Input beam parameters:  $\lambda=355$  nm,  $\theta_0=0.1$  mrad, and  $z=100$  m,

$$W_0 = \lambda/\pi\theta_0 = 1.13 \text{ mm}, \quad z_0 = W_0/q_0 = 11.3 \text{ m}.$$

Pre-collimation lens parameters:  $f_0=50$  cm.

$$M_0 = \sqrt{\frac{f_0^2}{(f_0 - z)^2 + z_0^2}} = 4.993 \times 10^{-3},$$

$$W'_0 = W_0 \cdot M_0 = 5.642 \times 10^{-4} \text{ cm}, \quad \theta'_0 = \theta_0/M_0 = 20.03 \text{ mrad}, \quad z'_0 = W'_0/\theta'_0 = 0.028 \text{ cm},$$

$$z'_p = f_0 + M_0^2 \cdot (z - f_0) = 50.25 \text{ cm}.$$

Beam size at the plane of  $z_l=60$  cm:

$$W = W'_0 \sqrt{1 + \left( (z_l - z'_p) / z'_0 \right)^2} = 0.195 \text{ cm}.$$

Beam size at the plane of  $z_l=70$  cm:

$$W = W'_0 \sqrt{1 + \left( (z_l - z'_p) / z'_0 \right)^2} = 0.395 \text{ cm}.$$

## **II: Vertical beam design**

Input beam parameters:

$$W_0 = 5.642 \times 10^{-4} \text{ cm}, \theta_0 = 20.03 \text{ mrad}, z_0 = 0.028 \text{ cm}, z=10 \text{ cm}.$$

Target beam parameters:

$$\lambda=355 \text{ nm}, W_{\perp}=0.2 \text{ mm}, \theta'_0 = \theta_{\perp} < 3 \text{ mrad}, (\text{we assume } \theta'_0 = \theta_{\perp} = -1.5 \text{ mrad})$$

$$W_0' = \lambda/\pi\theta_0' = 7.53 \times 10^{-3} \text{ cm}, z_0' = W_0'/\theta_0' = 5.02 \text{ cm}.$$

### **Telescope design**

(1)  $f_1=-50 \text{ cm}$  (concave cylindrical lens).

$$M_1 = \sqrt{\frac{f_1^2}{(f_1 - z)^2 + z_0^2}} = 0.833,$$

$$W_0'' = W_0 \cdot M_1 = 4.70 \times 10^{-4} \text{ cm}, \theta_0'' = \theta_0/M_1 = 24.05 \text{ mrad}, z_0'' = W_0''/\theta_0'' = 0.02 \text{ cm}, z_1 = f_1 + M_1^2 \cdot (z - f_1) = -8.367 \text{ cm}.$$

(2)  $f_2=12.5 \text{ cm}$  (convex cylindrical lens),  $d=5 \text{ cm}$ ,  $z_2=d-z_1=13.367 \text{ cm}$ .

$$M_2 = \sqrt{\frac{f_2^2}{(f_2 - z_2)^2 + z_0''^2}} = 14.414,$$

$$W_0' = W_0'' \cdot M_2 = 6.775 \times 10^{-3} \text{ cm}, \theta_0' = \theta_0''/M_2 = 1.67 \text{ mrad}, z_0' = W_0'/\theta_0' = 4.06 \text{ cm}, z' = f_2 + M_2^2 \cdot (z_2 - f_2) = 192.63 \text{ cm}.$$

(3) To achieve beam size  $2W_{\perp}=0.4 \text{ mm}$ , the distance from the telescope to the interaction region will be:

$$z_l = z' - z_0' \sqrt{(W_{\perp}/W_0')^2 - 1} = 181.35 \text{ cm}.$$

Distance from the first cylindrical lens  $L_{\perp} = d + z_l = 186.35 \text{ cm}$ .

Distance from the pre-stage lens  $L = L_{\perp} + z + z_p' = 246.6 \text{ cm}$ .

### **III: Horizontal beam design**

Input beam parameters:

$$W_0 = 5.642 \times 10^{-4} \text{ cm}, \theta_0 = 20.03 \text{ mrad}, z_0 = 0.028 \text{ cm}, z=20 \text{ cm}.$$

Target beam parameters:

$$\lambda=355 \text{ nm}, W_p=5 \text{ mm}, \theta_0'=1 \text{ mrad},$$

$$W_0' = \lambda/\pi\theta_0' = 0.0113 \text{ cm}, z_0' = W_0'/\theta_0' = 11.3 \text{ cm}.$$

### **Telescope design**

(1)  $f_1=-50$  cm (concave cylindrical lens).

$$M_1 = \sqrt{\frac{f_1^2}{(f_1 - z)^2 + z_0'^2}} = 0.714,$$

$$W_0'' = W_0 \cdot M_1 = 4.03 \times 10^{-4} \text{ cm}, \theta_0'' = \theta_0/M_1 = 28.05 \text{ mrad}, z_0'' = W_0''/\theta_0'' = 4.75 \times 10^{-3} \text{ cm},$$

$$z_1 = f_1 + M_1^2 \cdot (z - f_1) = -14.3 \text{ cm}.$$

(2)  $f_2=22.5$  cm (convex cylindrical lens),  $d=9$  cm,  $z_2=d-z_1=23.3$  cm.

$$M_2 = \sqrt{\frac{f_2^2}{(f_2 - z_2)^2 + z_0''^2}} = 28.12,$$

$$W_0' = W_0'' \cdot M_2 = 0.011 \text{ cm}, \theta_0' = \theta_0''/M_2 = 1.0 \text{ mrad}, z_0' = W_0'/\theta_0' = 11.3 \text{ cm},$$

$$z' = f_2 + M_2^2 \cdot (z_2 - f_2) = 655.1 \text{ cm}.$$

(3) At  $z_l = L - z_p' - z - d = 167.35$  cm,

$$W = W_0' \sqrt{1 + \left( (z_l - z')/z_0' \right)^2} = 0.49 \text{ cm}.$$

Distance from the first cylindrical lens  $L_p = d + z_l = 176.35$  cm.

## IV: Optical pulse intensities at intersection planes

Assume (i) the telescopes are outside of the vacuum and (ii) the distance of the vacuum window to the light-particle interaction region is 50 cm.

### **(1) Pre-collimation Lens**

Beam radius at the lens plane:  $w_{L0}=1$  cm,

Optical pulse intensity at the lens:

$$I_{L0} = E_{\text{pulse}} / p W_{L0}^2 = 150 \text{ mJ} / (p' 1 \text{ cm}^2) = 0.05 \text{ J/cm}^2.$$

### **(2) Vertical Telescope**

Beam size at the first cylindrical lens:

$$W_{P,L1} = W_{\perp,L1} = 5.642 \times 10^{-4} \times \sqrt{((60 - 50.25)/0.028)^2 + 1} = 0.20 \text{ cm},$$

Optical pulse intensity at the first cylindrical lens:

$$I_{\wedge,L1} = E_{\text{pulse}} / p W_{P,L1} W_{\wedge,L1} = 150 \text{ mJ} / (p' 0.2' 0.2 \text{ cm}^2) = 1.2 \text{ J/cm}^2.$$

Beam size at the second cylindrical lens:

$$W_{P,L2} = W_{\perp,L2} = 5.642 \times 10^{-4} \times \sqrt{((65 - 50.25)/0.028)^2 + 1} = 0.30 \text{ cm},$$

$$W_{\perp,L2} = 4.7 \times 10^{-4} \times \sqrt{(13.367/0.02)^2 + 1} = 0.31 \text{ cm}.$$

Optical pulse intensity at the first cylindrical lens:

$$I_{\wedge,L2} = E_{\text{pulse}} / p W_{P,L2} W_{\wedge,L2} = 150 \text{ mJ} / (p' 0.3' 0.31 \text{ cm}^2) = 0.5 \text{ J/cm}^2.$$

### **(3) Horizontal Telescope**

Beam size at the first cylindrical lens:

$$W_{P,L1} = 5.642 \times 10^{-4} \times \sqrt{((70 - 50.25)/0.028)^2 + 1} = 0.40 \text{ cm},$$

$$W_{\perp,L1} = 6.775 \times 10^{-3} \times \sqrt{((192.63 - 5)/4.06)^2 + 1} = 0.31 \text{ cm},$$

Optical pulse intensity at the first cylindrical lens:

$$I_{P,L1} = E_{\text{pulse}} / p W_{P,L1} W_{\wedge,L1} = 150 \text{ mJ} / (p' 0.4' 0.31 \text{ cm}^2) = 0.39 \text{ J/cm}^2.$$

Beam size at the second cylindrical lens:

$$W_{P,L2} = 4.03 \times 10^{-4} \times \sqrt{(23.3/4.75 \times 10^{-3})^2 + 1} = 1.98 \text{ cm},$$

$$W_{\perp,L1} = 6.775 \times 10^{-3} \times \sqrt{((192.63 - 14)/4.06)^2 + 1} = 0.30 \text{ cm}.$$

Optical pulse intensity at the first cylindrical lens:

$$I_{P,L2} = E_{\text{pulse}} / p W_{P,L2} W_{\wedge,L2} = 150 \text{ mJ} / (p' 1.98' 0.30 \text{ cm}^2) = 0.08 \text{ J/cm}^2.$$

#### **(4) Vacuum Window**

Beam size at the vacuum window:

$$W_{P,V} = 0.011 \times \sqrt{((167.35 - 50 - 655.1)/11.3)^2 + 1} = 0.54 \text{ cm},$$

$$W_{V,L1} = 6.775 \times 10^{-3} \times \sqrt{((181.35 - 50 - 192.63)/4.06)^2 + 1} = 0.10 \text{ cm}.$$

Optical pulse intensity at the vacuum window:

$$I_{V,L1} = E_{\text{pulse}} / p W_{V,L1} W_{V,L1} = 150 \text{ mJ} / (p' 0.54' 0.1 \text{ cm}^2) = 0.88 \text{ J/cm}^2.$$

